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Flowability of granular materials with industrial applications

An experimental approach

Joel Torres-Serra[1,2,⋆], *Enrique* Romero[2], *Antonio* Rodríguez-Ferran[2], *Joan* Caba[1], *Xavier* Arderiu[1], *Josep-Manel* Padullés[1], and *Juanjo* González[1]

[1] *Técnicas Mecánicas Ilerdenses, S.L.*
[2] *Universitat Politècnica de Catalunya*

Abstract. Designing bulk material handling equipment requires a thorough understanding of the mechanical behaviour of powders and grains. Experimental characterization of granular materials is introduced focusing on flowability. A new prototype is presented which performs granular column collapse tests. The device consists of a channel whose design accounts for test inspection using visualization techniques and load measurements. A reservoir is attached where packing state of the granular material can be adjusted before run-off to simulate actual handling conditions by fluidisation and deaeration of the pile. Bulk materials on the market, with a wide range of particle sizes, can be tested with the prototype and the results used for classification in terms of flowability to improve industrial equipment selection processes.

1 Introduction

Within the industry of bulk material handling, bagging machinery is designed and manufactured to store and transport granular materials. This equipment can carry out dosing of powders and grains through gravimetric feeder systems among others [1], which consist of a batch weighing device that has to be fed on an adjustable flow of granular matter downstream a reception hopper.

The feeder selection process is still a challenging issue nowadays. Different types of feeding solutions exist, which mainly include:

- free discharge by gravity feeders or rotary valves;
- positive displacement by either belt, screw or vibratory tray feeders;
- pneumatic transport using fluidisation chambers.

The output rates of the feeder systems are affected by irregularities in dry granular flows, as well as the quality of the produced bags and the overall performance of the lines, evidenced through the formation of jamming processes even leading to stable arching or ratholing structures [2–4].

In turn, distinct material properties are shown by the diversity of products on the market and which are crucial in establishing the suitability of each bulk handling equipment. The lack of a standard framework for the industry as per flowability assessment of powders and grains demonstrates a need for experimental methodologies that are able to simulate actual handling conditions [5, 6].

⋆e-mail: j.torres@tmipal.com

Figure 1. Retained mass fractions of a refractory mortar sample after sieve analysis with sieves of mesh sizes 500, 200, 140, 100 and 71 μm (ISO 3310-1:2000 Series)

2 Methods

2.1 Testing techniques

The behaviour of granular materials can be described by means of the effect of both micro-scale and macro-scale properties on the mechanics of flow regimes [7]. At the particle level, the effect of parameters such as size, shape and density has been reported [8–10]. Complexity of the materials with actual industrial application is illustrated in figure 1, showing grain size dispersity of a refractory mortar sample by sieve analysis. Also, the granular shape of a food additive obtained by optical microscopy can be seen in figure 2.

At the bulk scale, robust characterization measures include compressibility in terms of uniaxial compression stress or flow factors obtained from shear testing in the quasi-static regime [11]. Rheological properties of granular materials are investigated to describe flowability of dense phases, including mixing and avalanching procedures [12, 13]. Also, indentation or penetrometry tests are

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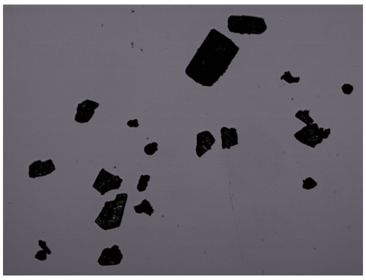

Figure 2. Projected particle shapes for image analysis of a food additive sample (d_{50} = 231 μm) mounted on a digital microscope at 4 optical magnifications

used to describe cohesive behaviour [14]. Furthermore, methodologies with a more indirect interpretation exist despite involving traditionally used parameters for instance discharging rates, compressibility in terms of tapping densities, angles of repose or dustiness [15–18], the latter being representative of dilute flows. Analysis of the aerated flow regime is also conducted via bulk permeability and bed expansion tests [19, 20].

In addition, the environmental conditions of granular flows have an effect on their behaviour. Hygroscopicity of bulk materials, essentially governed by the surface condition of constituent particles [21], is measured through relative humidity of surrounding air, water activity of the particles and equilibrium moisture content of the substance [22]. Some attempts have been made to incorporate temperature monitoring into flow testers [23]. What is more, exposure time to humidity and temperature conditions, as well as sampling of the materials, control among others caking processes, which alter flowability [24].

2.2 Granular column collapse

In recent years, granular column collapse experiments have been the object of study in a strive to better understand dry granular flows with implications, not only to earth sciences, but also to industry [25].

Figure 3 shows the test set-up, consisting of a container where a particle assembly is held. Once the granular column is formed, the container is instantaneously removed and the granular material is let spread out driven by gravity. Flow dynamics is mostly governed by interparticle contacts over particle-wall interactions [26].

The test yields direct observation of the kinematics of generated mass flows, thus focusing on the overall characterization of dense and dilute flow regimes beyond isolated measurements of bulk material and particle properties.

The initial configuration of the pile is adjusted regarding two main aspects:

- Geometry, considering quasi-two-dimensional and axisymmetric layouts [27, 28]. Inspection in the cylindrical case requires cutting the pile vertically to observe the effect of collapse on the final deposit, while the bulk remains unobservable during run-off. Semiaxisymmetric geometries have been explored to circumvent such drawbacks [29].
- Packing state, considering air fluidisation of the samples before release of the unsteady flow of powders and bulk solids [30].

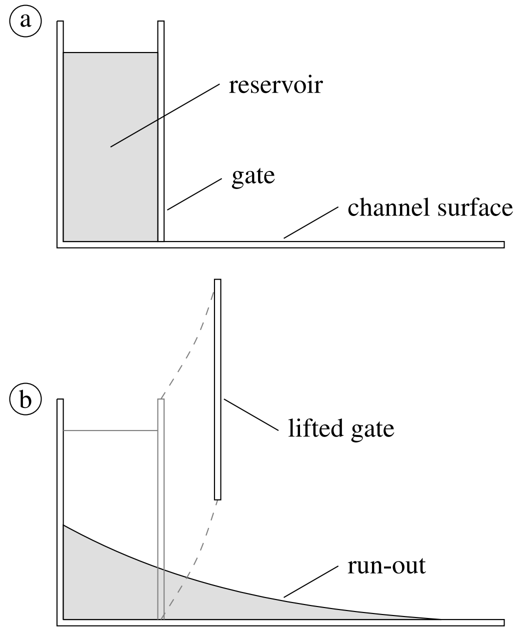

Figure 3. Schematic of a quasi-two-dimensional granular collapse test set-up: a) Initial configuration; b) Final deposit.

Further exploration of this methodology includes analysis of the effect of moisture content [31] or testing collapse on inclined planes [32].

3 Prototype

3.1 Proposal

A new prototype has been developed to provide insight into the mechanics of industrially produced powders and bulk solids based on run-out experiments. Various existing apparatus on the market aimed at the characterization of different flowability states are compared and their main features shown in table 1, in contrast with the capabilities of the new prototype. Traditional testers are not taken into account for comparison, despite being commercially distributed [33]. The objective is to reproduce the dynamic behaviour of granular samples in actual handling processes involving the release of material from a container at different packing conditions determined by the feeding systems in use.

Table 1. Comparison between proposed flowability prototype and commercial devices

	Prototype	Static testers [34]	Rheometers [35]	Dynamic testers [36]
Shear properties		•	•	
Compressibility	•	•	•	
Permeability	•		•	
Dynamic energy profile			•	
Dynamic morphology	•			•
Dynamic load pattern	•			•
Characteristic velocities	•			

3.2 Description

Figure 4 shows the assembly of the prototype. A quasi-two-dimensional arrangement is considered for better inspection of the tests regarding bulk velocity fields through lateral walls and longitudinal morphology and load distribution during run-off. Therefore, the device consists of a 2000 mm long, 160 mm wide horizontal channel with and anodized aluminium plate at the base and vertical glass walls with a height of between 350 and 150 mm, accounting for flow front height decrease due to propagation as well as for accessibility purposes during operation. A reservoir of a square 150 mm sided base and 350 mm wall height is attached to the channel in order to contain granular columns with aspect ratios going from 1 to 2 times the initial height with respect to the base length of the reservoir.

A lifting gate allows for instantaneous material release from the reservoir into the channel. It is made of carbon fibre reinforced polymer components held together by a 3D-printed polymeric frame as a means to lighten the mechanism. Motion of the gate is controlled by pneumatic valve actuators in two phases. First, fast horizontal separation from the vertical free surface of the column allows for the onset of flow; second, the gate is slowly withdrawn out of the reservoir and channel to clear vertical space for run-out visualization.

At the reservoir base, an air chamber allows for both air injection and suction for fluidisation and deaeration of the pile. The aerated state is representative of industrial processes such as pneumatic conveying and fluidisation chamber feeding. In this sense, previous reported experience has addressed quasi-static characterization [37]. The testing procedure considers gravity-driven flows at three different initial packing states:

- poured random packing as a result of free fall of granular material into the reservoir;
- loose packing obtained from poured packing by an imposed airflow —between minimum fluidisation and bubbling pressure [38]—into the poured material to observe aeration behaviour prior to the gate activation;
- dense packing resulting from deaeration of initially poured packing so as to evaluate air permeability of the different materials, which is a common technique applied in bagging systems.

To this end, injected air flows come out of an air compressor and into an air dryer, from where they are transported and regulated by a flowmeter, before being delivered to the air chamber, which in turn includes a manometer; air suction is imposed by inverting the air flow sense throughout the system. A permeable polyester needle-punched felt layer prevents particles of sampled materials from entering the air chamber, as used in actual industrial equipment.

At the channel base, logarithmically-spaced beam load cells (Modelo 104, UTILCELL, Spain) are installed to register dynamic load distributions to track the evolution of the stress state of the bulk at the channel surface. Power supply of the force transducers includes signal conditioning (SWIFT PANEL, UTILCELL, Spain).

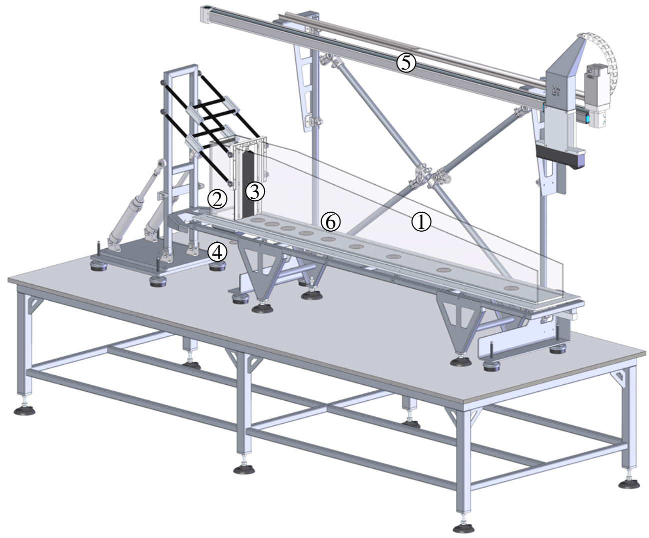

Figure 4. View of the prototype with numbered parts: 1) Channel; 2) Reservoir; 3) Lifting gate; 4) Air chamber; 5) Linear guide and laser scanner mount; 6) Membranes and load cell mounts.

Moulded silicone membranes placed at the channel base undergo small elastic deformations during run-off and, consequently, transmit dynamic reaction forces to the load cells.

Moreover, a 2D/3D laser scanner (GOCATOR 2150, LMI Technologies Inc, Canada) is mounted on a linear guide aligned with the channel and with positioning control by servomotor. The profile sensor provides three-dimensional maps of the final configuration for morphology analysis of the run-out. On the one hand, the quasi-two-dimensional assumption of the experiment can be checked. On the other hand, different shape patterns of the resulting deposits related to intrinsic bulk properties can be extracted, including measurement of traditional parameters such as the angle of repose [39].

Finally, a high speed video camera (PXW-FS5, SONY Corporation, Japan) is incorporated into the assembly of the prototype. The use of high speed digital video recording systems and image analysis post-processing techniques, such as the Particle Image Velocimetry [40], enables the extraction of relevant properties from the visualization of the established two-dimensional wall velocity field and flow patterns during run-off. Additionally, image analysis through column height monitoring is also used for measurements of compressibility by uniaxial compression using weights and bed expansion by air fluidisation.

4 Concluding remarks

Few previous experiences with granular column collapse of fine or cohesive powders are reported in existing research literature, typically resorting to monodisperse glass beads. A wide range of powders and bulk solids are dealt with in the packing industry, produced by several industrial sectors, namely the food, agri-food, construction and mining, chemical and petrochemical, and recycling industries.

Decision making strategies towards selecting the adequate machinery often rely on qualitative estimations of the flowability of granular materials, thus lacking a robust physical approach to mass flow phenomena. The presented prototype is intended to test bulk materials with particle sizes from the scale of micrometres to millimetres to provide a new flowability assessment methodology and, at the same time, allow the effect both particle and bulk properties have on the observed behaviour to be identified.

Results coming from prototype testing are to be used for defining a classification tool for any granular material of interest to the packing industry, based on establishing flowability clusters from properties that control regularity of product feed rates. Thus, a new methodology is to be introduced, leading to the choice of the most adequate feeder system for each material among the existing solutions presently in use.

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